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Energy consumptions and associated greenhouse gas emissions in operation phases of urban water reuse systems in Korea

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A B S T R A C T

Water reuse systems have been widely implemented across the globe as a solution to water shortage and freshwater contamination. Ongoing controversies regarding supposedly high energy cost and the lack of sufficient data to support benefits of water reuse are delaying further expansion of implementation of water reuse systems in South Korea. In order to clarify the ambiguity regarding the energy demand and provide an unbiased comparison between the water reuse alternatives and the conventional water supply system, energy consumptions and greenhouse gas emissions in operation phases of different water reuse facilities and the conventional water supply system were examined. The average total energy consumption and the greenhouse gas emission of the conventional process were calculated to be 0.511 kWh/m^3 and 0.43 kgCO$_2$e/m^3, respectively. Centralized wastewater reuse systems had prohibitively high energy consumptions (1.224–1.914 kWh/m^3) and greenhouse gas emissions (0.72–0.83 kgCO$_2$e/m^3). The decentralized wastewater reuse systems, greywater reuse and rainwater harvesting systems, all used for non-potable purposes, had comparable or higher energy demands than the conventional process (0.246–0.970 kWh/m^3 after adjustment), although estimated greenhouse gas emissions from these processes were lower than the conventional process (0–0.33 kgCO$_2$e/m^3 after adjustment). Considering the hidden environmental benefit (0.357 kWh/m^3) from reduction of contaminant release, the energy demand of greywater reuse drops far below that of the conventional system, suggesting that decentralized water reuse is the key to an energy-efficient water management with minimal impact on climate change.

1. Introduction

Since the onset of the industrialization era, rapid population growth and industrialization have led to various problems regarding water management. Across the globe, increased demand for water has led to water shortage both in residential and industrial sectors (García-Montoya et al., 2016; Yang and Abbaspour, 2007; Zhang et al., 2014) and the wastewater has deteriorated in quality and increased in quantity, threatening the quality of the freshwater bodies where it is released to (Friedrich et al., 2009; Rihon et al., 2002; Vince et al., 2008). As a result, the humanity is facing myriads of water-related problems and major improvements in water management strategies are indispensable for sustainable future (Alnouri et al., 2015; Bagatin et al., 2014; de Gois et al., 2015). South Korea has been traditionally known as a country with abundant water resources, as 58% of its land surface is covered with freshwater bodies including rivers, lakes, and reservoirs (MCT, 2011). Abundant rainfall (the 20-year average annual rainfall of 1277 mm is equivalent to 1.6 times the global average) has been characteristic of the region. Since the rapid industrialization that began in the 1960s, South Korea has developed into one of the most populous and industrialized countries in the world. As a result, South Korea now stands as one of the most water-stressed countries with 2669 m^3 of annual rainfall per capita, which is one-sixth of the world average (MCT, 2011). The annual water withdrawal in Korea currently amounts to an unsustainable 36% and South Korea is now categorized as a water-stressed country (Jiménez and Asano, 2008). Serious water shortage is expected in the near future, as a water deficit of 8900 tons/year is expected in the industrial sector alone by year 2020 (53.7% increase from 2007) and a total water deficit of 13,700 tons/year is expected by year 2025 (MCT, 2011).

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One of approaches of the Korean government to overcome this water crisis is to promote implementation of water reuse systems. Korean government has promulgated an environmental law enforcing incorporation of water reuse systems into designs of newly constructed buildings and wastewater treatment plants over certain capacities. The water reuse plan established in 2011 set a national goal of replacing 2.544 billion m^3/year of water supply (9.64% of the total projected water demand of 2020) with reclaimed water by 2020 (Ministry of Environment, 2011). The wastewater reuse rate has actually increased from 10.8% to 12.6% during the five-year span from 2009 to 2013 (Ministry of Environment, 2014). The use of greywater and rainwater has also increased by 2.8- and 2.2-fold during the same period, respectively (Ministry of Environment, 2014).

One of the barriers against further implementation of water reuse systems in South Korea has been apparent lack of data to convince the public and policymakers of the advantages of water reuse in terms of energy costs and greenhouse gas (GHG) emissions. Production and distribution of drinking water has always been an energy-intensive process and growing demands for water and increasingly more stringent water quality criteria have led to larger consumption of energy and increased GHG emission (Nair et al., 2014). Therefore, reduction of energy consumptions and GHG emissions has become one of the primary foci in establishing the blueprints for water management of the future (Del Borghi et al., 2013; Lundie et al., 2004). A few studies have been performed to compare energy demands and environmental impacts of conventional water infrastructures and water reuse systems, albeit with mixed results. Life cycle assessment (LCA) analyses of water management scenarios in Italy and Spain estimated generally higher energy consumptions for water reuse systems with tertiary treatment than conventional infrastructures (Amores et al., 2013; Del Borghi et al., 2013). On the other hand, Tong et al. (2013) reported that adoption of centralized wastewater reuse scheme in an industrial park can reduce life-cycle GHG emissions, due mainly to lower energy demand. Decentralized reuse systems, i.e., greywater reuse and rainwater-harvesting systems (RHS), have generally been perceived to be energy efficient; however, a compilation of empirical energy intensity data suggested an average energy demand of 1.40 kWh/m^3 for RHS, which was by far greater than the energy intensity of conventional water supply systems reported in the same study (0.22–0.80 kWh/m^3) (Vieira et al., 2014). Due to the paucity of reliable data and inconsistency of study results, policy makers (e.g., the Ministry of Environment in Korea) have casted doubts on the energy efficiency of the water reuse systems, and this dilemma is causing a delay in further implementation of the water reuse plan.

In this study, we tried to resolve this ambiguity by conducting a comparative analysis of energy consumptions and GHG emissions in conventional water supply systems and water reuse systems using actual operating data obtained from fully operational systems in South Korea. In order to ensure objectivity, assumptions and speculations were kept to minimum, and only the operation phase was examined to avoid problematic assumptions often made in LCA regarding construction and demolition phases, e.g., underestimation of the system life span (Stokes and Horvath, 2006). Also proposed here is a methodology to quantify intangible environmental benefits of water reclamation as energy gains.

2. Methods

2.1. Description of water reuse facilities

Water reuse systems vary in their sources, treatment capacity, end-use purposes and degrees and methods of treatment. The most common types of urban water reuse systems in Korea were represented with eight water reuse facilities carefully curated to cover this broad diversity (Table 1). Another important criterion for selection was the completeness of the available operation data, as a preliminary survey of more than 100 water reuse systems discovered that many water infrastructure facilities withhold their operation data from the public or have poor data collection systems.

The facilities P1, P2, and P3 are centralized wastewater reuse facilities producing deionized water through reverse osmosis (RO). Centralized wastewater reuse is often implemented to provide high-quality water to industrial complexes. These facilities are, in most cases, located at the sites of full-scale wastewater treatment plants and thus reclaimed water is transported through long supply pipelines to the consumers. In the surveyed facilities, the influent is pretreated with ultrafiltration (P1 and P3) or flocculation followed by disc filtration and vortex filtration (P2) before being introduced to RO for deionization. The reclaimed wastewater is provided to steel (P1) and paper factories (P2) and electronic components manufacturers (P3) through relatively long supply distances (1.9–11.5 km). These end use purposes require high purity that would require additional treatment if tap water is used. The facilities P4 and P5 are decentralized wastewater reuse facilities producing reclaimed wastewater for end-use purposes with less stringent quality requirement, e.g., toilet flushing, garden watering, and machinery cooling. The facility P4, located within the boundary of Incheon International Airport ground, treats wastewater collected from the airport and airplanes using an anaerobic-anoxic-oxic (A2O) activated sludge and sand/granule activated carbon (GAC) filtration followed by chlorination. The facility P5, installed in a shopping mall, treats wastewater generated within the building using a miniature A2O activated sludge and membrane filtration followed by ozonation.

The greywater reuse facility P6 is different from P4 and P5 in that its source water is separately collected greywater and thus, is contaminated to a lesser degree than ordinary wastewater. Source water for the facility P6 is collected exclusively from water sinks. The greywater is treated with virtually the same scheme as P5 and supplied back to the building for toilet flushing. These decentralized water reuse systems receive untreated wastewater or greywater as their source water. Thus, operations of these facilities would reduce the load onto existing wastewater treatment plants (WWTPs) and subsequent energy conservation was considered in the analyses.

The facilities P7 and P8 are rainwater harvesting facilities. The facility P7 is the largest rainwater harvesting facility in Korea with 106,029 m^2 and 12,000 m^3 as the area of the collection basin and the volume of the storage tank, respectively. Suspended solids in rainwater are removed by passing the collected rainwater through a suction strainer before temporary storage in a storage tank. The collected rainwater is then used for power plant operation after filtration. The overall treatment scheme of P8 is identical to P7. Rainwater is harvested on the roof catchment area (1372 m^2) and is collected in a storage tank (132 m^3) by gravity drainage. Collected rainwater is used for toilet flushing within the building after filtration.

2.2. System boundaries

The system boundaries for the water supply and reuse systems in this study were defined for objective comparison of energy costs and GHG emissions resulting from operation phases of the water infrastructures. For conventional water treatment, the system boundary was set to encompass abstraction, treatment and distribution. The system boundaries of water reuse schemes were determined to correspond to the system boundary of the